NAS8-36617
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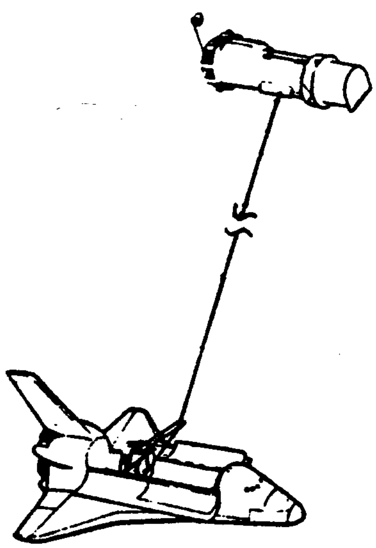
Phase III Study of Selected Tether Applications In Space

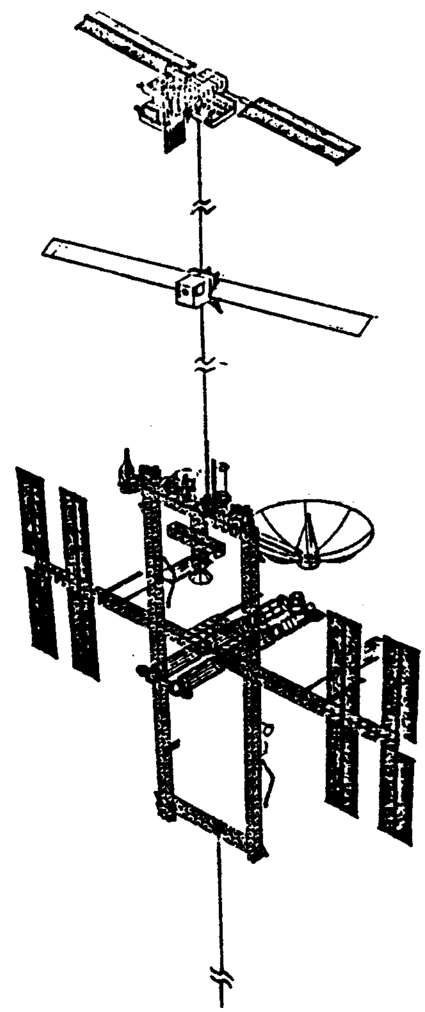
Contract: NAS8 – 36617
DPD 665 DR – 4

Final Report

Volume I – Executive Summary

December 1986





Prepared for:

George C. Marshall Space FLight Center
National Aeronautics and Space Administration
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(NASA-CR-179185) PHASE 3 STUDY OF SELECTED TETHER APPLICATIONS IN SPACE. VOLUME 1: EXECUTIVE SUMMARY Final Report (Ball Aerospace Systems Div.) 33 p Avail: NTIS HC A03/MF A01 CSCL 22B G3/18

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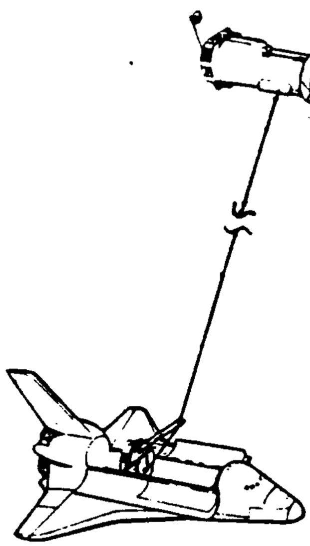

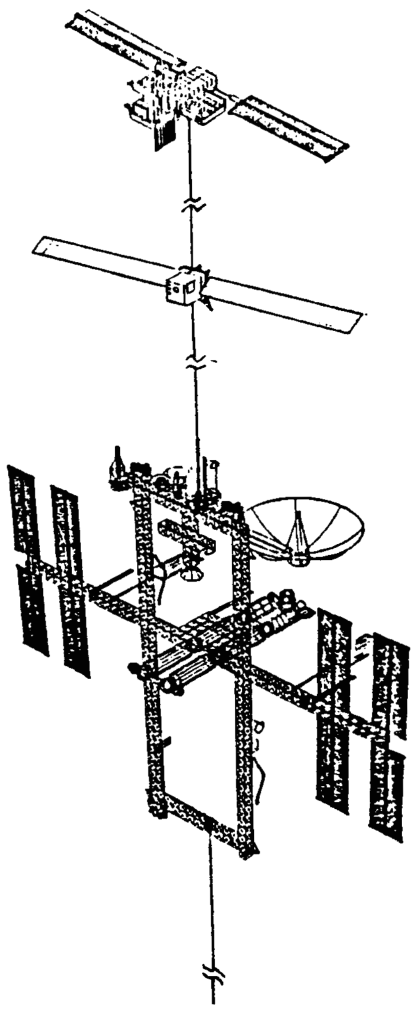

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FOREWARD

This study was accomplished by Ball Aerospace Systems Division (BASD) in the Space Systems business unit.

The Study Manager from October 1985 through January 1986 was Mr. Don Jones. The Study Manager from January 1986 through completion of the study was Mr. Dan McMann. Mr. Cal Rybak was responsible for initial cost sensitivity analysis, attitude control system design support, and tether sizing analysis for Shuttle based deployment missions. Mr. Ron Glickman was responsible for orbit dynamics analysis for tension only tether deployments from the Shuttle and for assessing the impacts of tethers on the micro-g level of the Space Station. Mr. Jim Byrnes contributed mechanical configurations and designs for the Space Station tether deployer, Shuttle Tether Deployer System (STEDS), mini-OMV (MOMV), and tether Crawler systems. Mr. Larry Murphy provided analysis support for power tether trades. Mr. Rex Sheppard provided analysis and design support for communications and data handling sub-systems. Mr. Tim Patton provided the cost estimates and LCC analysis. Ms. Jenny Ide provided support for cost modeling using a micro-computer work sheet. Mr. John Glaese of Control Dynamics Company provided analysis support for simulated tension only deployments. Mr. Tony Stroeve provided structural analysis support.

This summary is provided in accordance with Contract NAS8-36617, Data Procurement Document Data Requirement DR-4. The Technical Officer for this study was Mr. Jim Harrison, Marshall Space Flight Center, Huntsville, Alabama.

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1.0 INTRODUCTION

This report covers the results from study Phase III of a five phase NASA program to discover, understand, and develop applications for tethers in two general categories: (1) Tether Transportation Applications (TETRA) and (2) Tether Spacecraft Constellations (TESCON). In this report Item (1) addresses a tethered launch assist from the Shuttle for payloads with up to 10,000 kg mass for the mission model. Item (2) addresses the tethering of a 15,000 kg science platform from the Space Station. It also encompasses the design and cost analysis for a variable "g" device that could be placed on the tether and allow ultra-low "g" or other types of experiments to be conducted. This device would move up and down the tether as required to accomplish the experiments.

In the first two phases of the NASA program numerous tether applications were examined and their theoretical feasibility and technology requirements assessed. In this phase engineering designs are developed relative to (1) and (2) and these are used as the basis for a cost benefit analysis which assesses the feasibility of using such systems as a practical alternative to what would otherwise be accomplished by conventional means. The term "conventional" as related to both these applications is intended to apply to the use of some form(s) of chemical propulsion system.

This study is divided into two distinct types of tether applications. The first application allows a science platform to co-orbit with the Space Station without the large propellant requirements associated with stationkeeping the platform by conventional propulsive means. This same tether would provide a path for a Crawler system to move along. The Crawler would be capable of carrying a variety of payloads out along the tether to perform experiments in microgravity, variable gravity, plasma physics, materials science and other areas that could exploit the unique capabilities of this type of facility.

The second type of tether application involves using a tether system, positioned in the Shuttle bay, to launch payloads into higher energy orbits without the use of conventional propellant systems.

These tether applications were compared, on a cost basis, with competing conventional propulsion techniques. The following pages present a summary of the study results.

2.0 TETHERED PLATFORM AND CRAWLER STUDY

SCOPE

This portion of the study contract consisted of a cost benefit comparison between tethered and conventional propulsive methods of co-orbiting a 15,000 kg Science Platform with the Space Station. A 10 km tether was selected as being most representative of a practical stand-off distance from the Space Station.

Here the tether is used as an alternative to a separate propulsion system for the remote stationkeeping of certain co-orbiting experiments and payloads, which, because of their special nature or operating characteristics, cannot be co-located with the Space Station itself. For instance, isolation may be needed with respect to space Station contaminating effluents and energy fields as well as from Space Station vibrations and imposed coarse pointing capabilities. Alternately, Space Station compatible payloads and elements may have to be isolated from the effects of certain contaminating experiments such as one presently being proposed which would seek to characterize the effects of thruster plume plasmas on solar arrays. The term "co-orbiting" in the above is meant to imply that isolated payloads will nevertheless rendezvous with the Space Station, perhaps every few weeks, for servicing.

The initial phase of this trade study examined the technical implications of tethering such payloads to the Space Station as compared to using a free-flying platform with a conventional propulsion system. This was done primarily from the standpoint of achieving payload performance objectives and included studies relating to alterations of the micro-g environment and the ability to point accurately. The assessment of micro-g implications was further broadened during the study to encompass the unique zero-g and micro-g capabilities of a Tether Crawler System. Figure 1 illustrates the combined Space Station, tethered platform and Tether Crawler components.

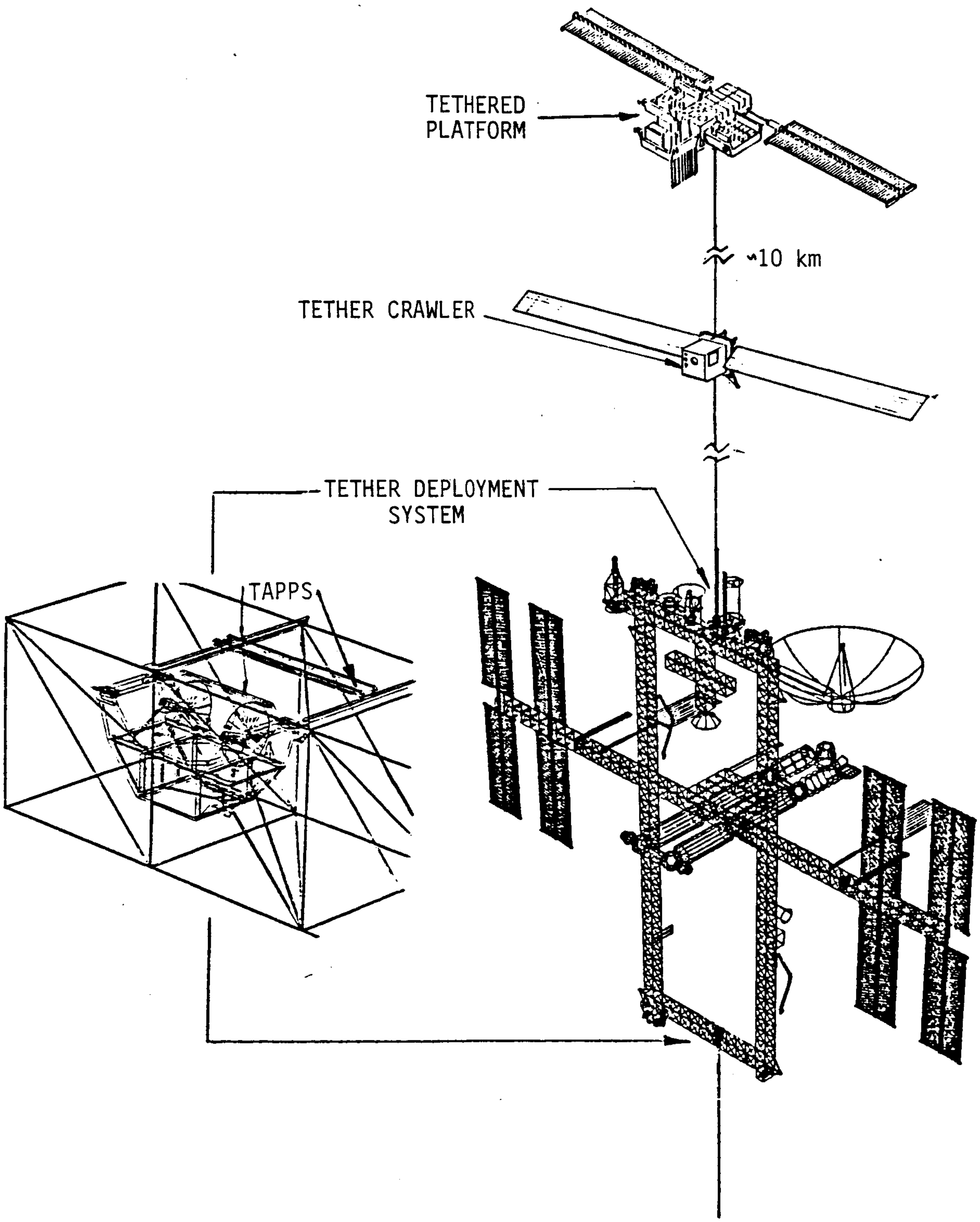


FIGURE 1 TETHERED PLATFORM SYSTEM ELEMENTS

In addition to the implications related to payload performance, the study also addressed the technical implications and cost associated with the Space Station viewed as a resource facility. This category included investigations related to using the tether as a conduit for transfer of both communications and electrical power. However, the primary area for cost comparison was associated with the additional fuel needed to stationkeep the Science Platform at a fixed distance from the Space Station. This cost was compared to accomplishing the same task utilizing the platform tethered from the Space Station.

Finally, the implications of tether operations on Space Station design, operational scenario, safety, and cost were investigated. This included studies related to the tether tension loading of the truss structure, the tether's effect on Shuttle docking procedures, its effect on Space Station attitude, and its effect on Station field-of-views.

A set of tether system and conventional system hardware designs were then developed to serve as models for the actual cost comparison process. The designs which evolved during this second phase were in many ways influenced by the results of the initial implication effects study phase, because every effort was made to define practical systems in which both tether and conventional system impacts with the Space Station were minimized. The studies and results related to the above two phases are detailed in Volume II of this report.

The third phase of the study involved the actual cost comparison analysis of the competing systems defined in phase two. This task was accomplished using the RCA PRICE cost modeling system and a Lotus-123 based life cycle cost (LCC) model. Details of this cost effort are presented in the separate cost document accompanying the study report (DR-6 Sections 2-16 thru 2-20 and its appendices.) A brief summary of the findings are presented here in the next section entitled Study Results.

STUDY RESULTS

This section briefly summarizes the major aspects of the hardware designs which evolved during the study, and the cost comparison figures which were arrived at after completion of the preliminary engineering designs.

Tether vs. Free-Flyer Platform Concepts

A dual tether system was selected as the only practical approach to tethering a Science Platform (see Figure 1), since a single platform tethered at several kilometers distance would so adversely affect the micro-gravity environment on the Space Station. Here a dummy mass which can be reeled in and out using its own deployer system, which essentially duplicates the primary system, supplies the necessary ballast to keep the CG near the Space Station habitat modules. Each deployer is a two-part system the first element of which consists of a carrier structure containing a reel, drive system, and tether level wind control. The second element is a Tether Alignment and Platform Positioning System (TAPPS) mechanism used for aligning the tether tension force through the Space Station CG when the Space Station is in its nominal nadir pointed attitude (see Figure 1).

The competing conventional system is a free-flying platform which incorporates an integral propulsion system for stationkeeping.

The cost comparison process yielded the following top level results relative to the above two concepts. (All figures are in constant 1987 dollars.)

DUAL TETHER DEPLOYER SYSTEM COSTS

Hardware Design and Development Cost	$ 22,244,000
Hardware Production Cost	$ 25,224,000
Operations and Support Cost	$ 64,514,168*
Software Cost	$ 2,102,500
Total Tether Deployer Cost	$114,084,668

*Note: Shuttle Launch Costs are $30,506,215

The costs associated with stationkeeping a free-flying platform are dominated by the cost of bringing the required propellants into orbit via the Shuttle. The estimated amount of propellant varies between 3,000 and 13,500 kg/year. The actual consumption is strongly dependent on the distance to which the platform is allowed to drift from the nominal standoff position plus the speed and accuracy at which the nominal standoff position is re-established during each drift cycle. The above range translates into yearly costs of $15M to $68M, for an average of $41.5M a year. This does not include operator and/or equipment costs needed to accomplish the stationkeeping. Thus the savings in using the tether concept amounts to at least $415M - $114M = $301M, over a ten year operating period.

It should be noted that a marginal costing technique has been applied above wherein only differences affecting bottom line cost comparison are identified. Thus, since the KITE system development costs associated with a tether application were judged to be roughly comparable to the cost of an attitude control system and propulsion system for a free-flyer, neither entry appears in the above.

Communications Tether vs. RF Link Concepts

The communications tether concept is a composite tether which includes a fiber optics cable to serve as the communications element and a Kevlar cable to serve as the structural element. The competing conventional system is a standard Ku band 2 watt solid state transmitter. Both systems were designed to permit Platform-to-Space Station and Space Station-to- Platform data rates of up to 50 Mbps when the separation distance is as much as 10 km.

Costs of $3,805,000 and $1,760,000 were computed for the fiber-optics and conventional systems, respectively when the separation distance was 10 km. At shorter distances the costs become more comparable until at one km, the fiber-optics system would cost about the same as a conventional system, the costs of RF system being essentially invariant over this range of separations. The communications tether is a more expensive alternative than the conventional RF approach, but it does offer some unique advantages. For instance, the optical Tether data transmission would be very secure for sensitive data.

Power Tether vs. Solar Array Power Concepts

The tether concept for using Space Station power consists of a two conductor system which uses a high voltage DC (4.5 kV) form of transmission. The alternate conventional concept is a standard solar array system proposed for use on the Space Station free-flying platforms.

The cost estimates produced using PRICE together with marginal weights are shown below. Note that these costs do not represent the total cost of the components, but only the marginal costs associated with increased requirements of the particular approach. For instance, both systems will need slip ring assemblies, but the power tether is assessed a marginal weight because of the increased complexity of high voltage slip ring assemblies. In some cases the weight indicates the total estimated weight (i.e., solar arrays) if the component is unique to one of the approaches. It will be noted that the apparent cost advantage of using a power tether is quite small ($832,000).

WEIGHT PENALTY (KG)

Component	Free-flyer	Power Tether	Marginal Cost ($K) Development Delta
Solar Arrays	580 kg	0	$10,274
Power Conditioning	0	100 kg	($7,839)
Tether Cable	0	850	($708)
Batteries	0*	0*	--
Slip Ring Assemblied	0	68 kg	($1,533)
Solar Array Drives	54	0	$4,180
Power Bus Regulation	0*	0*	--
Thermal Control	0	68	($1,280)
Totals	634 kg	1086 kg	$3,094
Transportation Weight Penalty		-452 kg	($2,262)
Net Cost Benefit Using a Power Tether			$832k

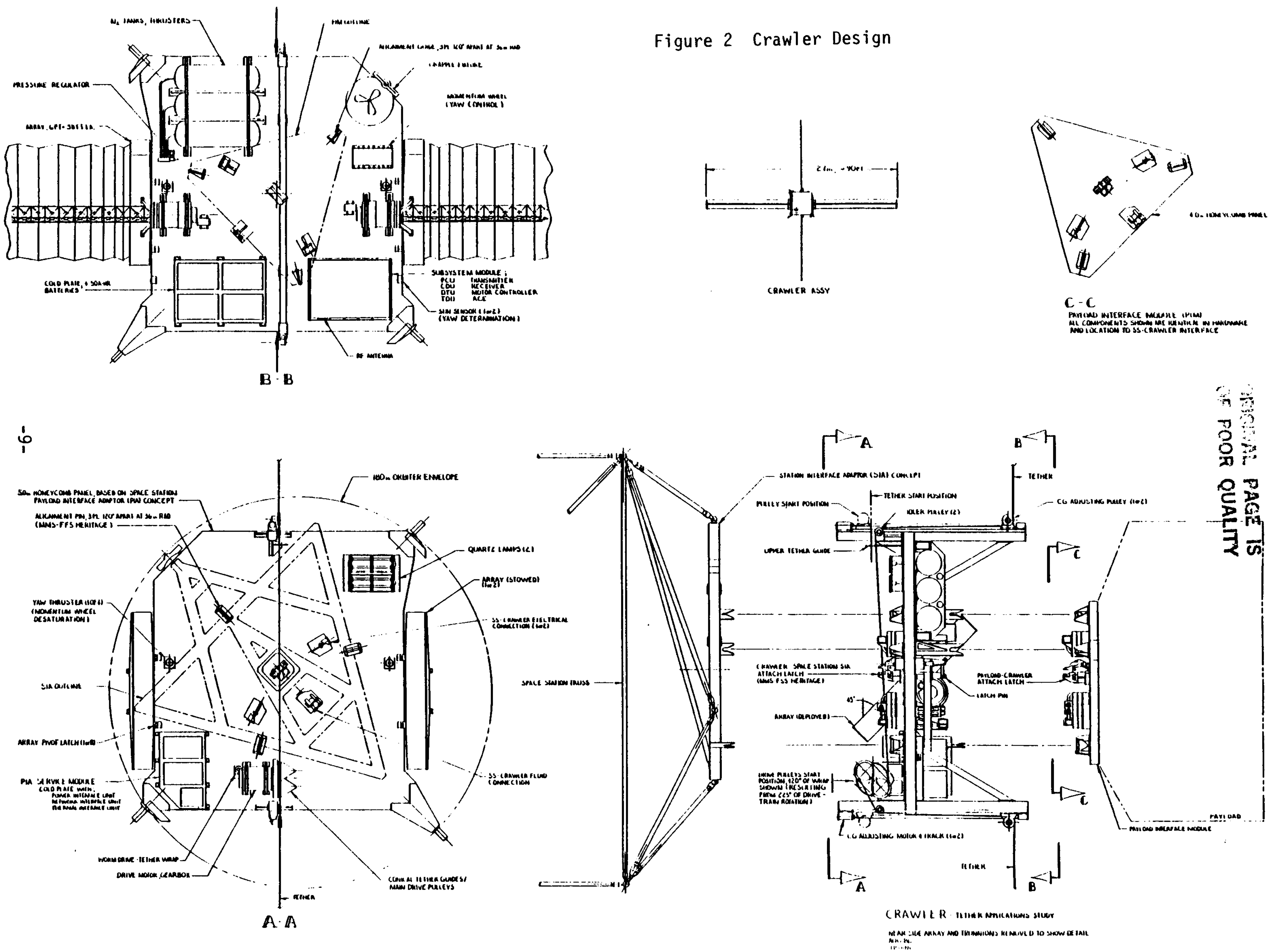
*indicates items considered equivalent in weight and cost for both approaches

Tether Crawler Concept

The approach taken relative to Crawler design is that it serve as a bus which can satisfy many experiment and mission objectives. These include its use as a vehicle to transfer and support payloads that want to operate in the vicinity of the Space Station (essentially a small tehtered platform), its use as a Space Station CG control device to offset the effects of Shuttle dockings, consummable movements, etc., and its use as variable-g or high quality micro-g laboratory.

The Crawler concept consists of a 2000 kg vehicle (including payload) capable of supplying 2000 watts average orbital power, and capable of transferring over tether distances of up to 100 km, with unattended "stay away" times of up to one year. Figure 2 illustrates the Crawler design arrived at in the study. Figure 1 illustrates the Crawler in use with the tethered platform, however this device could be employed with any deployed tether.

Figure 2 Crawler Design



This design concept was put through the RCA PRICE model and LCC costs were estimated. A summary of the costing results are presented below. Details of this cost effort are presented in the separate cost document accompanying this study report (DR-6 Sections 2-11 thru 2-15 and its appendices.)

TETHER CRAWLER SYSTEM COSTS

Hardware Design and Development Cost	$ 12,896,000
Hardware Production Cost	$ 19,617,000
Operations and Support Cost	$ 46,661,447*
Software Cost	$ 6,610,000
Total Crawler Cost	$ 85,784,447

*Note: Shuttle Launch Costs are estimated at $7,015,200 for a one-time launch.

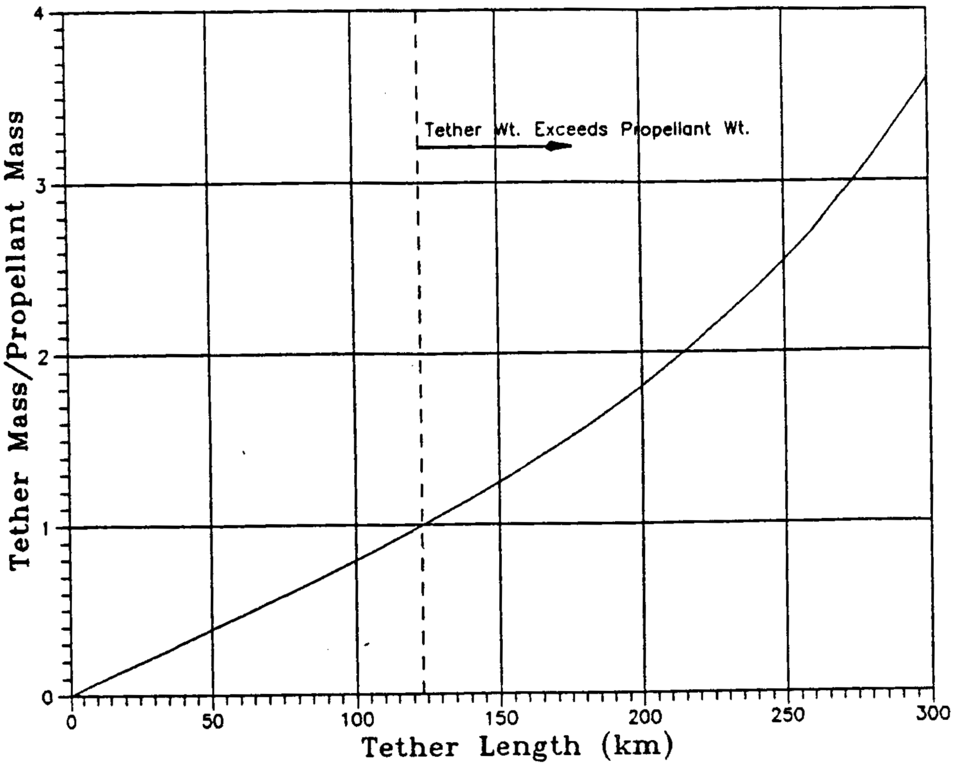
3.0 SHUTTLE TETHER TRANSPORTATION RESULTS

Tethers can be used in a transportation mode to insert payloads/satellites from an orbiting host vehicle (i.e. the Shuttle) to orbits that are significantly higher than that of the host. This part of the study examined the implications of tethered payload deployments from the Shuttle, the impact such deployment might have on shuttle operations and the cost benefits of tether deployments when compared to more conventional, i.e., propulsive techniques.

Tether Mission Analysis

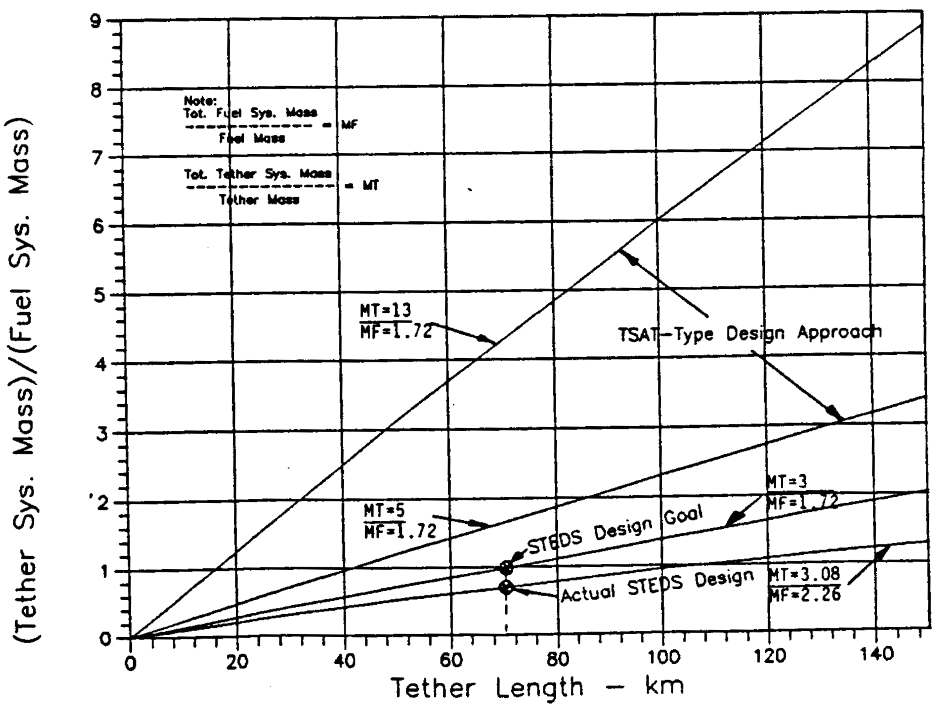
A variety of payloads have been proposed for tether assisted launches from the Shuttle. The payload sizes range from small experiment packages weighing a few hundred kilograms to AXAF weighing several thousand kilograms. The orbit altitude change associated with these proposed missions range from a few tens of kilometers to a few hundred kilometers. For system sizing and design a payload maximum weight of 10,000 kilograms was assumed for the study. This payload weight covers all but the largest Shuttle payloads in the near future. A limit can be placed on the maximum tether length that can be economically justified for payload deployment from Shuttle. This requires considering the tether weight versus the weight of propellant required to make an equivalent orbital transfer. It can be shown that this ratio is independent of the payload mass. This ratio is plotted in Figure 3a. It should be noted from this graph that for tethers longer than about 120 km the tether alone weighs more than the equivalent propellant (assumed to be hydrazine) to accomplish the same orbit change. This is an important limit since the launch weight of the system is the major cost contributor, especially for systems that will be launched many times and the launch cost is applied every time the system is used.

The total systems weight of the tether and propellant approaches must be considered to compare total launch costs. The propellant system will be heavier, and therfore more expensive to launch for tether lengths shorter than some maximum length which is independent of payload mass. Figure 3b shows the relation between the ratio of Tether system mass and propellant system mass



Ratio of Tether Mass to Propellant Mass to Accomplish Same Orbit Transfer

Figure 3a



Ratio of Tether System Mass to Fuel System Mass for Design

Figure 3b

for a variety of tether systems. The Tether systems with MT ratios of 5 to 13 represent TSAT type designs with reeling mechanisms. The propellant system MF of 1.72 is one proposed design for the Orbital Maneuvering Vehicle (OMV). The lower two curves refer to the design concept developed during this study. The design point for the tether system is indicated. The design point established for the STEDS system is 70 km of tether which will provide an equivalent circular orbit altitude change of 300 km from an initial Shuttle circular orbit of 300 km. The actual designs that resulted from this study are depicted by the lowest curve in Figure 3b. Note that refinements to this design would lead to tether lengths approaching 100 km being competitive on a weight basis.

Shuttle Tether Deployer System (STEDS)

A system to allow tether assisted launches from the Shuttle was designed and costed during this study. The design is presented in Figure 4. This system is designed to minimize operational costs and provide significant orbit raising capability to payloads up to 10,000 kg (22,000 lbs.).

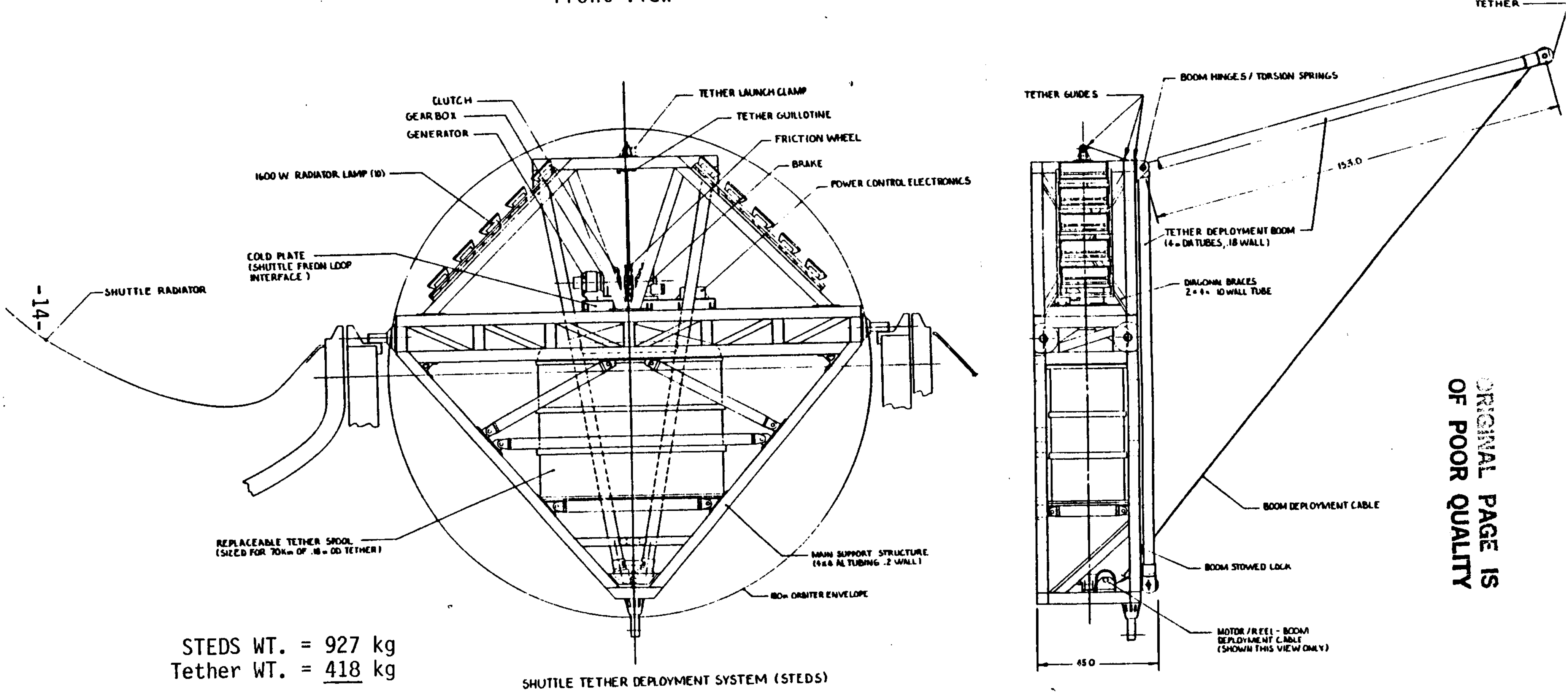
Early cost analysis indicated that launch costs are the most significant driver of total LCC. Therefore, the STEDS design minimizes the two parameters affecting launch cost most, system weight and cargo bay length occupied.

The weight of the system was reduced by using lightweight aluminum truss construction and adopting a deployment scenario that eliminates several heavy components and simplifies the STEDS operations. The deployment is controlled by back tension in the tether and some limited Shuttle Reaction Control System (RCS) firings. This deployment approach eliminates the need for bi-directional motor control and the reel and level wind mechanisms like those proposed for the Tethered Satellite program. The tether is expendable in this design approach and would be replaced after each mission.

The adoption of a tension only deployment also allows the STEDS length in the Shuttle bay to be minimized. The tether is stored in a compact canister instead of on a bulky reel mechanism to further reduce the required Shuttle Bay length.

Front View

Side View



STEDS WT. = 927 kg
Tether WT. = 418 kg
Total Sys. 1345 kg

Figure 4 STEDS Design

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The tension line-of-action, relative to the Shuttle center of ass (CM) must be controlled to keep the tether from impacting the Shuttle structure or other payloads in the bay. This is accomplished by the use of a deployable boom. This same boom could be used to control the Shuttle attitude during the deployment by compensating for in-plane librations of the tether.

When a payload is deployed from the Shuttle energy is generated that must be dissipated. The amount of energy generated is a function of the tether length and the peak power level is a function of the deployment rate. The peak power is the design driver for the STEDS control system. Figure 5 shows the variation in power level for 3 different deployment timelines of 8, 12 and 24 hours. Note that the highest power requirement occurs for the 8 hour deployment.

STEDS dissipates the deployment energy by converting it into electrical energy using a generator. The electrical energy is then directed to a series of high temperature quartz lamps where it is converted to heat and radiated to space. The generator also serves as the tension generating device for tether control. Figure 6 illustrates the design of the STEDS tension control system.

The operational sequence used during STEDS assisted payload deployment is shown in Figure 7. The actual STEDS sequence begins after the payload has been checked out and removed from the bay with the RMS. The STEDS boom is deployed and the payload is attached to the tether. The RMS then releases the payload and small RCS firings are used to back the Shuttle away from the payload and establish the initial gravity gradient forces in the tether. The remainder of the deployment sequence is controlled by the back tension developed in the STEDS generator/pulley arrangement. At the end of deployment the astronaut sends a command to STEDS that cuts the tether and the deployment is complete. The payload end of the tether will be automatically released when a relaxation is the tension in detected. The tether should re-enter the earths atmosphere and burn up within a few weeks.

The STEDS boom is re-stowed after the deployment and the system is returned to Earth, in the Shuttle bay, for refurbishment and re-flight.

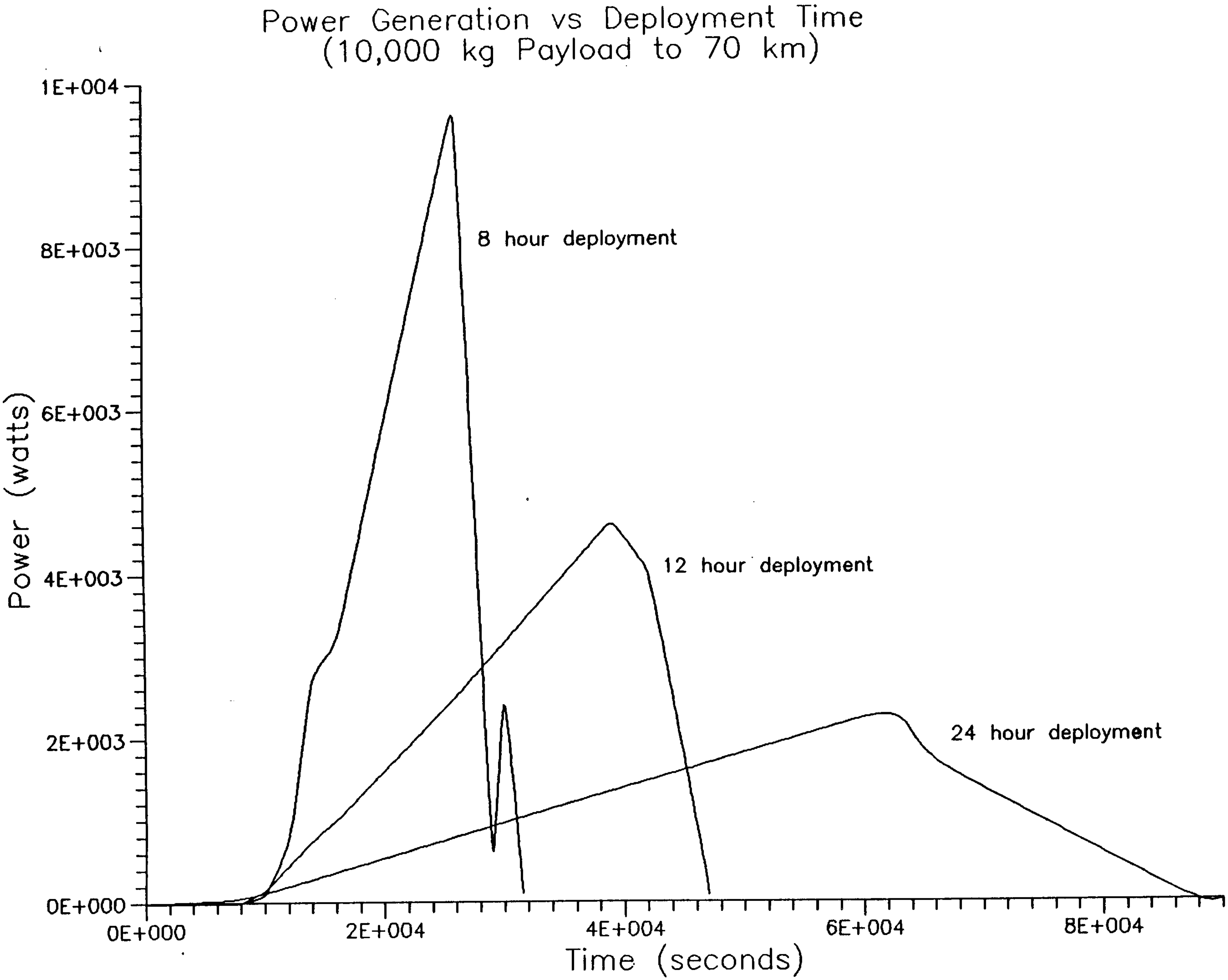

Figure 5 Power Generation vs. Deployment Ti[illegible] (10,000 kg Payload to 70 km)

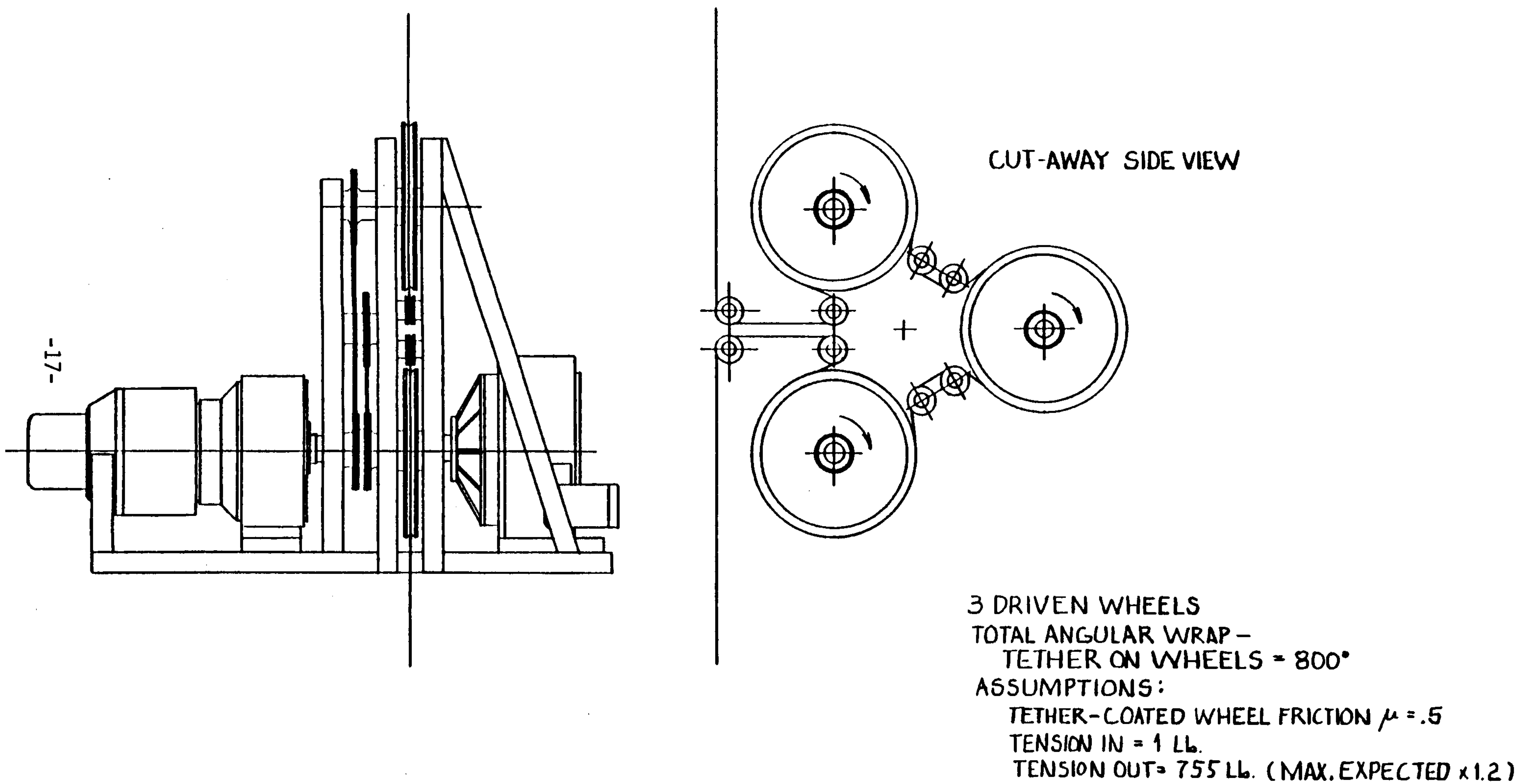

Figure 6 STEDS Tether Deployment Control Concept

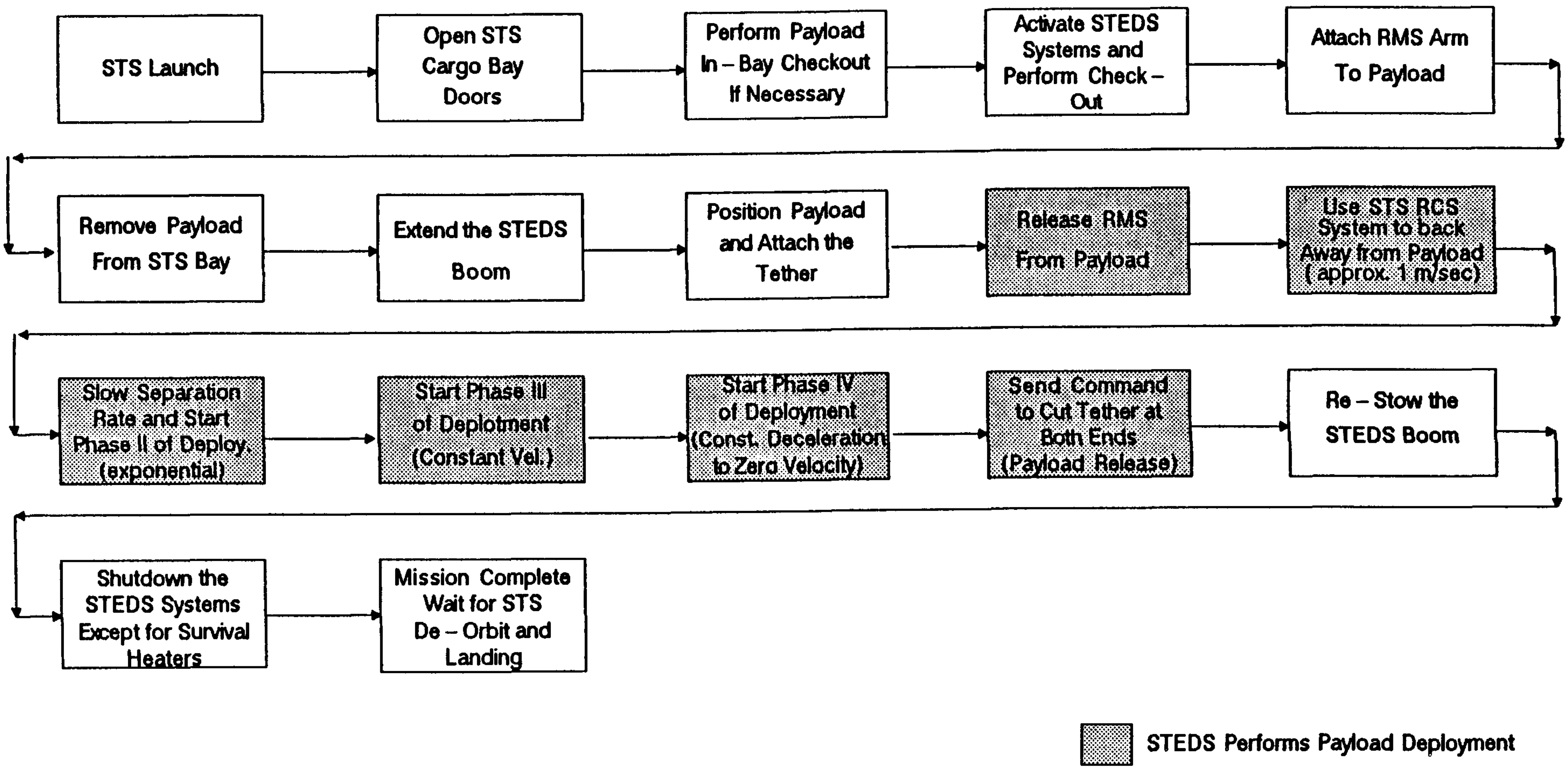

Figure 7 STEDS Operational Sequence

The estimated program and operational cost for a STEDS type Shuttle payload deployment system are presented below.

Hardware Design and Development	$ 8,928,000
Hardware Production Cost	$ 7,382,000
Operations & Support Cost	$276,248,476
Software Cost	$ 2,102,500
	$294,660,976

The important thing to note from these costs is that the operations cost, which includes an assumed 25 shuttle re-flights over a 10 year period, accounts for over 93% of the total costs. The Shuttle launch costs are estimated to be $262M for the 25 flights which is 90% of the total LCC.

MOMV Design

One of the main tasks of this study was to evaluate the cost benefit of using tethers to accomplish payload orbit altitude increase versus conventional means of accomplishing the same task. To establish a baseline to measure the cost benefit from, it was necessary to establish a conventional means of accomplishing the orbit transfer. To this end BASD designed a hypothetical conventional system whose only function was moving payloads from the Shuttle altitude to a higher circular orbit. The propulsion system was sized to give approximately the same orbit transfer capability as the STEDS system. BASD refers to this competing conventional system as a mini-Orbital Manuevering Vehicle (MOMV), since it is essentially a scaled down version of the NASA proposed OMV for Space Station activities. Figure 8 is an illustration of the proposed conventional propulsion alternative to the STEDS system.

The MOMV is attached to the payload on orbit in a manner similar to that of the STEDS described earlier. However, for this concept the MOMV and payload are both removed from the bay once they have been attached together using the MOMV latches. This combination is then released by the RMS and the Shuttle fires its RCS thrusters and moves a safe distance from the MOMV/Payload stack. The MOMV sub-systems are then activated and the MOMV begins a low thrust spiral ascent to the payload drop off altitude.

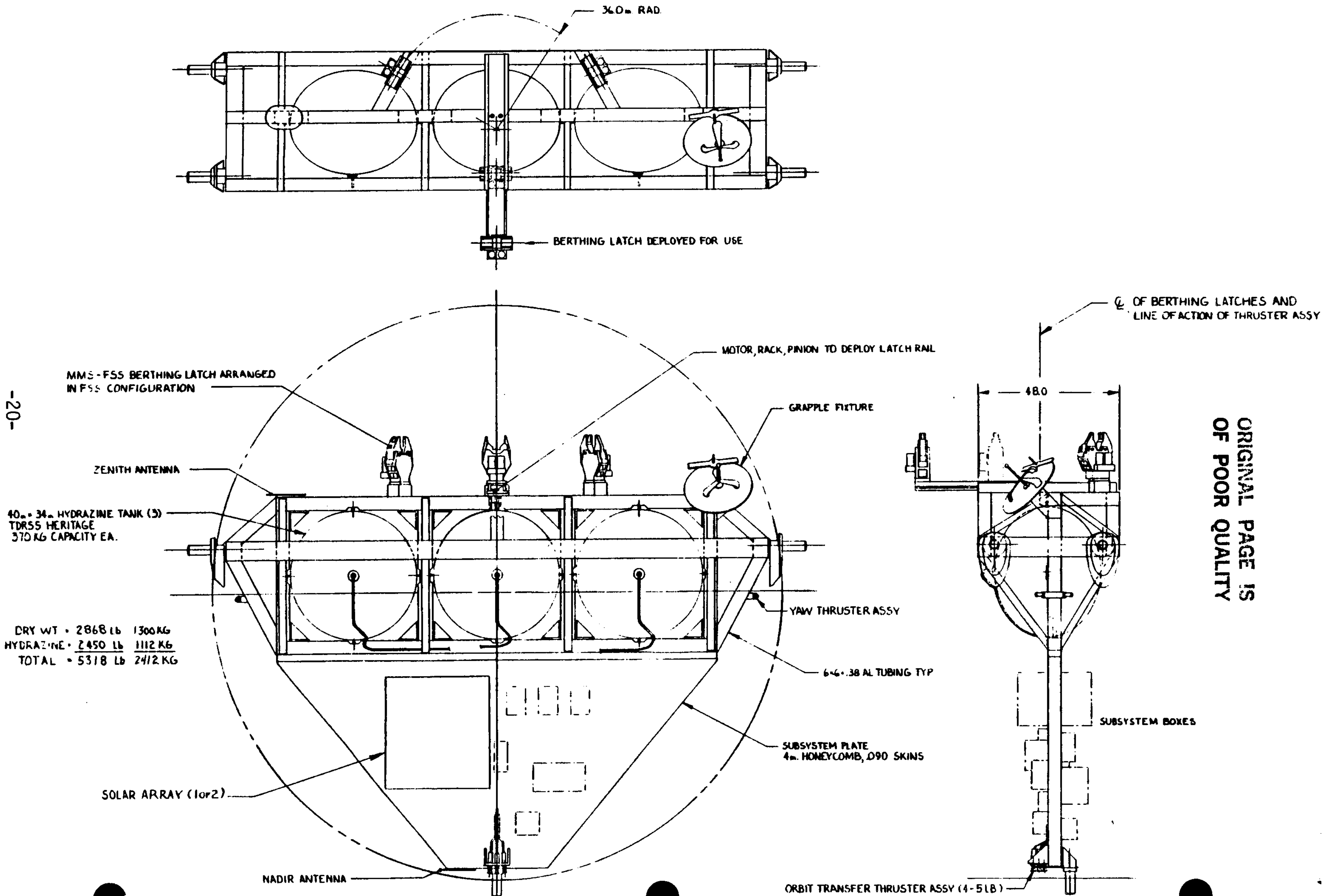

Figure 8 Mini-OMV Layout

At the dropoff altitude the payload is released from the MOMV and the MOMV returns to the Shuttle altitude. Once in the vicinity of the Shuttle the MOMV systems are shutdown and the Shuttle performs a rendezvous with the MOMV. Then the RMS is used to retrieve it and place it back in the bay. The MOMV is then returned to earth for refurbishment and re-flight.

A cost model was developed for this competing "conventional" system with the following results:

Hardware Design & Development Cost	$ 13,019,000
Hardware Production Cost	$ 15,345,000
Operations and Support Cost	$315,175,000
Software Cost	$ 4,025,000
Total MOMV Cost	$347,564,000

Again the operations cost is the driver for the total LCC. The Shuttle launch costs alone are estimated at $296M for the proposed 25 mission lifetime. Comparing these numbers with the costs for STEDS presented earlier indicates the tether system has a LCC advantage of about $53M. However, a large percentage of this is in the operations area (about $39M) which could easily be erased by a small increase in the bay length chargeable to STEDS. This might be necessary if the proposed canister shape for the tether proves unfeasible during a detailed design effort. Therefore, the cost of the two approaches must be considered equivalent within the error bounds of the analysis and design assumptions. The cost analysis did confirm the importance of weight and bay length in any tether system design that is going to be launched repeatedly in the Shuttle bay.

4.0 CONCLUSIONS OF TETHER APPLICATIONS IN SPACE STUDY

4.1 TETHER TRANSPORTATION MISSIONS FROM SHUTTLE

a) The design, development and test cost for the STEDS hardware is approximately one half of the cost of the MOMV, i.e. $18M vs $32M.

b) The life cycle cost (LCC) of either the STEDS or the MOMV is so dominated by operations, particularly launch costs, that the total hardware procurement costs represent less than 10% of total LCC and is insignificant in terms of a cost differentiator between the two systems

c) The STEDS, as the design is presently conceived, has a slight launch cost advantage relative to the MOMV primarily due to its shorter length which translates into LCC operational advantage over the MOMV. If total LCC is compared the STEDS has a 15% cost advantage over the MOMV or $295M as opposed to $348M, a $53M cost differential. However, it must be noted that the cost differential indicated is probably within the error band of the relative costing numbers and its significance is diminished as a criterion for determining whether the STEDS or the MOMV should be developed as an alternative payload transportation system from the Shuttle.

d) Even if a 15% cost advantage could be realized using a tether deployment system it is doubtful that it could compete with conventional propulsion techniques when one considers the flexibility of conventional propulsion and the orbit insertion accuracies that could be achieved, and the risks associated with tether deployment.

e) A tether deployer from the Shuttle would be a viable contender for situations where a MOMV type propulsion stage could not be employed to transport a payload from the Shuttle standard orbit due to contamination or some other reasons requiring that the Shuttle insert the payload by direct ascent. However, the economic viability of developing a tether deployer for such cases would depend on the number of payloads that fit into this category.

4.2 TETHERED PLATFORM

a) Tethering a platform to the Space Station will essentially eliminate the stationkeeping fuel required by a co-orbiting platform. The amount of fuel this represents depends upon the accuracy with which the co-orbiting platform orbital parameters can be established relative to the Space Station and the difference in ballistic coefficients between the platform and Space Station. If the orbital parameters can only be set to the accuracies obtainable by GPS then a "reasonable" amount of fuel could be saved which translates into meaningful cost savings. However, the fuel and hence cost savings are reduced if other techniques in addition to the GPS system (e.g. ranging relative to the shuttle, timed engine burns, etc.) are employed to more accurately establish the orbital parameters of the co-orbiting platform relative to the Space Station.

b) Tethering the co-orbiting platform to the Space Station will adversely affect the micro-gravity environment on the platform. It is apparent that for tethers on the order of 10 km the "g" level on the platform will exceed those desired by most microgravity experiments. Shortening the length of the tether although reducing the "g" level on the platform will reduce the stability of the tethered platform system since the tension in the tether will also be reduced. This can lead to safety problems if the length of the tether is significantly reduced from a nominal 10 km length.

c) The tension loads applied to the Space Station structure will require that the truss structure be strengthened. The preliminary analyses indicated that the amount of strengthening required will result in a significant increase in the weight of the proposed Space Station structure. Increased production and transportation costs will result due to the increased structural weight. However, it should be noted that if there is a requirement that the Space

Station accommodate tethered payloads including platforms then the cost for strengthening the Space Station truss structure should not be charged to the tethered platform.

d) Due to the adverse effect of tethering on platform "g" level it is apparent that a tethered platform would primarily house astrodynamic or possibly earth pointing experiments as opposed to materials processing experiments. Although relatively precise pointing control accuracies can be achieved by the use of the KITE system, there is a viewing time problem with some astrodynamic payloads. The maximum viewing time that are expected on an inertial target is 1/2 orbit before a reacquisition must be initiated in order to avoid the tether wrapping around the platform. Many astrodynamic payloads require viewing times considerably in excess of 1/2 orbit in order to integrate sufficient light energy to form acceptable images. This requirement would result in the need to gimbal those payloads allowing them to remain inertially fixed during platform re-acquisition adding to the payload integration cost.

e) Both the tethered and free flying platforms have virtually identical sensing systems if they are to achieve equally precise pointing performance. Although the free flying platform would require a propulsion system, the tethered platform would also require a propulsion system to provide attitude stabilization in the event of a tether failure. It is also anticipated that there will be a cost equivalence between the KITE actuation system on the tethered platform and the momentum exchange actuation system aboard the free flyer. Additionally, the power, communication, and thermal control systems on a tethered verses free flying platform will also be equivalent. However, the tethered platform needs a reeling mechanism capable of both deployment and retrieval which is not required by the free-flying platform. A dual system will be necessary if micro-g conditions are to be maintained on the Space Station. The reeling mechanisms will increase the hardware acquisition costs of a tethered platform over the equivalent free-flyer by $54M.

f) Items b) thru e) need to be countered balanced against the possible fuel savings that could be realized as described in item a) and at present it seems that a tethered platform is a reasonable economic choice.

4.3 COMMUNICATION TETHER

The results of this study indicate that using a fiber optic cable for communication between the tethered platform and Space Station is not cost effective until very high data rates, beyond those specified for the free flying platforms, are realized. Even at elevated data rates it appears that there isn't a significant cost difference between a conventional communication system and a fiber optic tether. When one factors fiber optic development, programmatic and operational risk it does not appear that it is an economically viable alternative to the conventional approach.

4.4 POWER TETHER

The results of this study indicate that the power tether may be marginally cost competitive with a conventional solar panel power system. The power tether shows a cost benefit of $832k, but given the high risks and many unknowns of developing this type system it is not possible to come to a definite conclusion about the economic viability of this system. This is due primarily to the inability to properly assess the amount and type of micrometeroid protection required by the high voltage tether to prevent arcing from damaged insulation and the development and production costs for high voltage slip ring assemblies.

It should also be noted that the $832K cost advantage identified for the power tether assumes that the tethered platform is treated as an attached payload. This treatment implies that the 10 kw of power needed by the tethered platform is supplied from the baseline Space Station power system without adding any supplemental solar panel capacity to the Space Station to compensate for the loss of the 10 kw power capacity that a free flying platform would add to the Space Station constellation. If an additional 10 kw of solar panel capacity would be added to the Space Station keeping the total power capacity of the constellation constant the power tether would be approximately $10M more costly than the conventional solar panel power system.

4.5 CRAWLER SYSTEM

a) The crawler system (i.e. lab) can be used as a variable "g" lab, however, unreasonably long tethers would be required to reach "g" levels in the order of 10^{-2} a number quoted by the community interested in variable "g" experimentation.

b) The design, development and build of the crawler system is approximately $35M and an evaluation needs to be made whether the cost is worth the return.

5.0 RECOMMENDED FUTURE EFFORT

As a result of the studies performed, the data obtained and the conclusions drawn from that data the following tasks are recommended as a continuation to the efforts described in this report.

Crawler as a Variable "g" Lab and Mass Balancer

1. The Crawler concept has significant potential both as a variable gravity lab and mass balancer for the Space Station capable of placing the Space Station CM at a desired location within relatively broad bounds. The use of a Crawler as a variable "g" lab should be further investigated by performing the following:

   (A) Detailed investigations of the experiment types that require variable "g" environment and the characteristics of these experiments.

   (B) Group the experiments into reasonable payload compliments and derive the resource requirements for the Crawler if these experiments were mounted on it.

   (C) Examine whether these experiments can reasonably be performed on the core Space Station by using the Crawler as a mass balancer placing the CM of the Space Station-tether combination at various points relative to the core Space Station.

   (D) Refine the Crawler system design in accordance to the above generated requirements and update its cost. Also define the Crawler system design and cost that would only act as a mass balancer allowing the experiments to be performed on the core Space Station, and compare them with the variable "g" lab Crawler configuration and determine which concept is more cost effective in meeting experiment requirements.

2. The use of a Crawler to compensate for Space Station CM movements due to internal mass motions such as fluid transfers, and the docking of the STS and other elements that may be serviced by the Space Station should be investigated by performing the following tasks.

   (A) Determine the maximum CM excursions at the Space Station due to internal mass motion and the docking of logistic/servicing elements.

   (B) Define the Crawler system characteristics/requirements that will compensate for the expected Space Station CM motions.

   (C) Design and develop the cost of a Crawler system that will compensate for the expected Space Station CM variations.

   (D) Design, develop and cost a conventional type tether system with ballast weight that could compensate for the expected shuttle mass motions, compare those to the Crawler system and specify the tether configuration that would be most cost effective in compensating for Space Station CM motion.

(E) Determine the additional cost that would be incurred if the tether mass balancing system would simultaneously act as a variable "g" lab and determine whether such a concept is economically viable.

Investigation of SEDS Deployment Technique

The basic problem with the economic viability of the tether as a transportation device from the STS is its size and weight when compared to a conventional propulsion stage. The SEDS deployment technique holds the potential of significantly reducing the tether system size and weight, thereby making it more competitive with conventional propulsion techniques. The following tasks should be performed to establish the economic viability of the SEDS deployment technique.

A) Define the SEDS deployment sequence/technique and determine the requirements placed on the STS, particularly in terms of propellant consumption.

B) Determine the sensitivity of the SEDS deployment technique to various system errors and determine the sensitivity of orbit insertion accuracies to these errors.

C) Determine techniques/control system configuration that would reduce orbit insertion errors due to system error sources.

D) Design and cost a SEDS tether deployment system and determine its cost effectivity relative to conventional propulsion techniques.

Use of a Tether for Plasma Measurements

Simultaneous measurements of plasmas, atmospheric densities and other orbital parameters at varying altitudes from which gradients can be determined has been of interest to the scientific community for many years. A tether system containing various sensors deployed along its length is uniquely suited and probably the only reasonable way to make such measurements in a cost effective manner. The following tasks should be performed to determine the configuration of a tether plasma measuring system.

A) Determine the type of plasma/orbital parameter measurements that are of interest.

B) Define the types of sensors available to make the required measurements.

C) Determine the techniques by which such sensors could be mounted along the tether length and establish the tether plasma measurement system deployment sequence.

D) Design and cost a tether plasma measurement system.

Further Investigations of Space Station Tethered Platforms

The results of the present study indicate that tethering a science platform to the Space Station has economic merit if the orbital parameters cannot be adjusted any better than the capabilities represented by the GPS system, and that the KITE system performs as projected. However, there are a number of areas that need further investigation to establish whether the economic advantage presently projected is in fact the case. These investigations are:

A) Definition of the accuracies with which a co-orbiting platforms orbital parameters could be adjusted using other aids such as Space Station radars timed burns, etc., in addition to the GPS system, and define the hardware and operation cost of these additional aids.

B) Design and cost of a KITE system that will achieve the desired platform pointing performance.

C) Define the impact on the KITE system design if a power tether is used requiring that power be transferred across the KITE interface.

D) Determine the additional payload integration hardware (particularly gimballing systems and their associated component/electronics) that would be needed to allow payload viewing of a single source for indefinite time periods and develop costs for these systems. Compare these costs to the payload integration hardware needed for a free-flyer and determine the cost differential between the two approaches.

E) Determine the additional structural Space Station weight that would be required to accommodate a tethered platform and establish whether this additional weight and cost will be absorbed by the Space Station program.

F) Based on the above data, refine the determination of the economic viability of tethered vs. free flying platforms.

Dynamic Model Verification

Numerous dynamic models of varying degrees of complexity have been formulated to describe the behavior of tether systems. These models give varying results for the dynamic behavior of the same tether system and, at present, there is no good way of determining which descriptions adequately describe tether behavior. In addition the present tether modeling/simulation capability is better than the accuracy with which system and environmental parameters can be specified. It is therefore apparent that tether orbital flight experiments need to be formulated and flown that will verify tether dynamic behavior and yield data that will enable more accurate specification of system and environmental parameters.

It is recommended that the following tasks be performed to specify and fly a tether flight experiment that will result in the data needed to verify the results of tether dynamic simulation and enable accurate specification of system and environmental parameters.

A) Determine the system and environmental parameters that have "large" degrees of uncertainty and define the types of measurements needed to establish more accurate values.

B) Determine the technique by which tether dynamic behavior could be accurately established and define the types of measurements and measurement accuracies needed to perform this function.

C) Define the system configuration that will perform the desired measurement described in items "A" and "B".

D) Perform a preliminary design of the tether experiment system and determine the system cost including launch, launch vehicle, flight operations and data reduction. Using this data define a phase C/D program that will meet with budgetary constraints and still yield the data in a timely fashion.

E) Perform the detail design, fabrication and test of the tether experiment system.

F) Fly the tether experiment system, obtain/reduce the data and define tether dynamic behavior and system/environmental parameters.

G) Input the more accurate system and environmental parameters into the various dynamic models for tether systems and establish the degree of fidelity of each.